Precise (fixed-order) predictions for vector-boson scattering

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29 February 2024, İzmir

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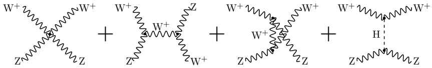
Reminder: what is vector-boson scattering?

1. production of two EW gauge bosons (usually $\mathrm{W}^{\pm}/\mathrm{Z}$)
2. together with two jets
3. with decays at $\mathcal{O}(\alpha^6)$ (LO)

4 categories for fully leptonic decays:

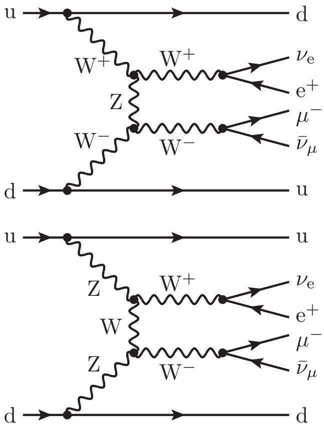
- $\mathrm{pp} \to \mathrm{W}^{\pm}\mathrm{W}^{\pm}\mathrm{jj}$: like-sign scattering
- $\mathrm{pp} \to \mathrm{W}^{\pm}\mathrm{Zjj}$: WZ scattering
- $\mathrm{pp} \to \mathrm{ZZjj}$: ZZ scattering
- $\mathrm{pp} \to \mathrm{W}^{+}\mathrm{W}^{-}\mathrm{jj}$: opposite-sign scattering

$\mathcal{M}^{\mathrm{WZ}}_{\mathrm{VBS}} =$

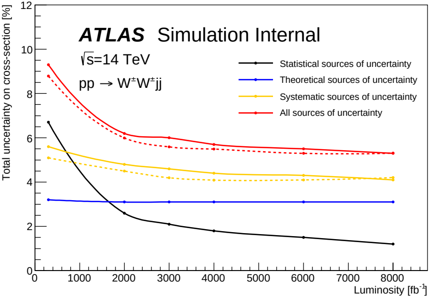


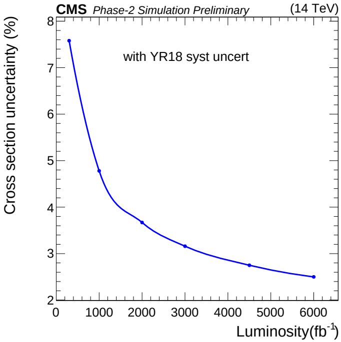
- QGC at LO (with VVV production)
- Higgs-V-V couplings and Higgs usually off-shell
- Probe EW symmetry breaking

2 → 6 opposite-sign VBS:



How precise do we need our calculations to be?

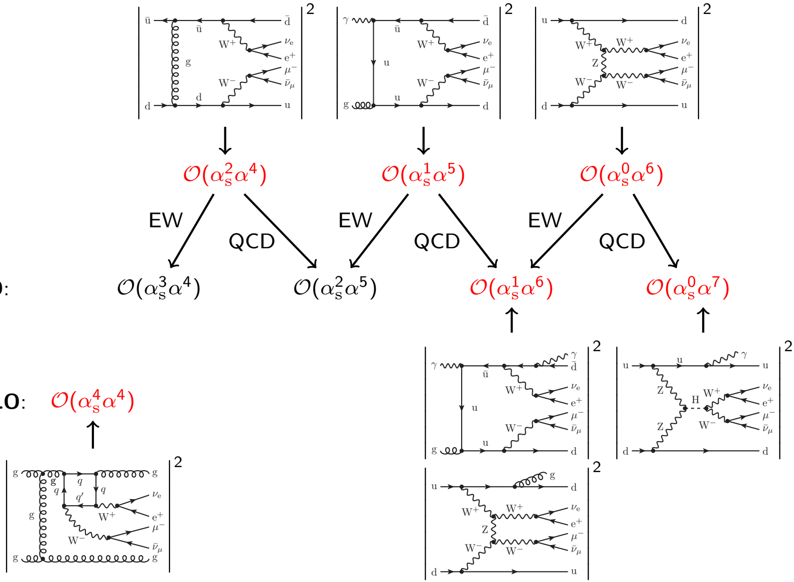




- plots from [P. Azzi et al.]
- CMS: only statistical and experimental systematic uncertainties
- for the integrated cross section for $\mathrm{W}^+\mathrm{W}^+$ NLO predictions will be needed
- NNLO not needed yet (pfew!)

What have we got to calculate?

Fixed-order tower for $\mathrm{W^+W^-}$ scattering:



LO: $\mathcal{O}(\alpha_s^2\alpha^4)$ $\mathcal{O}(\alpha_s^1\alpha^5)$ $\mathcal{O}(\alpha_s^0\alpha^6)$

EW QCD EW QCD EW QCD

NLO: $\mathcal{O}(\alpha_s^3\alpha^4)$ $\mathcal{O}(\alpha_s^2\alpha^5)$ $\mathcal{O}(\alpha_s^1\alpha^6)$ $\mathcal{O}(\alpha_s^0\alpha^7)$

NNLO: $\mathcal{O}(\alpha_s^4\alpha^4)$

Part I. VBS channels with fully leptonic decays

Status of fixed-order predictions for fully leptonic VBS

$$\begin{tikzcd}
\textbf{LO}: & & \mathcal{O}(\alpha_s^2\alpha^4)^{\checkmark} \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \mathcal{O}(\alpha_s^1\alpha^5)^{\checkmark} \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \mathcal{O}(\alpha_s^0\alpha^6)^{\checkmark} \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & \\
\textbf{NLO}: & \mathcal{O}(\alpha_s^3\alpha^4)^{\checkmark} & & \mathcal{O}(\alpha_s^2\alpha^5) & & \mathcal{O}(\alpha_s^1\alpha^6)^{\checkmark} & & \mathcal{O}(\alpha_s^0\alpha^7)^{\checkmark}
\end{tikzcd}$$

$(\mathrm{W^+W^+}, \mathrm{ZZ})$

First fully off-shell calculations:

- $\mathrm{W^+W^+}$:
    - [T. Melia, K. Melnikov, R. Röntsch, G. Zanderighi]: $\mathcal{O}(\alpha_s^3\alpha^4)$
    - [B. Biedermann, A. Denner, M. Pellen]: $\mathcal{O}(\alpha^7)$
    - [B. Biedermann, A. Denner, M. Pellen]: $\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s\alpha^6)$ and $\mathcal{O}(\alpha_s^2\alpha^5)$
- $\mathrm{W^+Z}$:
    - [F. Campanario , M. Kerner , L.D. Ninh , D. Zeppenfeld]: $\mathcal{O}(\alpha_s^3\alpha^4)$
    - [A. Denner, S. Dittmaier, P. Maierhöfer, M. Pellen, C.S.]: $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_s\alpha^6)$
- ZZ:
    - [F. Campanario , M. Kerner , L.D. Ninh , D. Zeppenfeld]: $\mathcal{O}(\alpha_s^3\alpha^4)$
    - [A. Denner, R. Franken, M. Pellen, T. Schmidt]: $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_s\alpha^6)$
    - [A. Denner, R. Franken, M. Pellen, T. Schmidt]: $\mathcal{O}(\alpha_s^2\alpha^5)$
- $\mathrm{W^+W^-}$:
    - [T. Melia, K. Melnikov, R. Röntsch, G. Zanderighi]: $\mathcal{O}(\alpha_s^3\alpha^4)$
    - [A. Denner, R. Franken, T. Schmidt, C.S.]: $\mathcal{O}(\alpha^7)$ and $\mathcal{O}(\alpha_s\alpha^6)$

LO fractions

Different setups with $\Delta y_{\mathrm{j_1 j_2}} > 2.5$ and $M_{\mathrm{j_1 j_2}} > 500\,\mathrm{GeV}$:

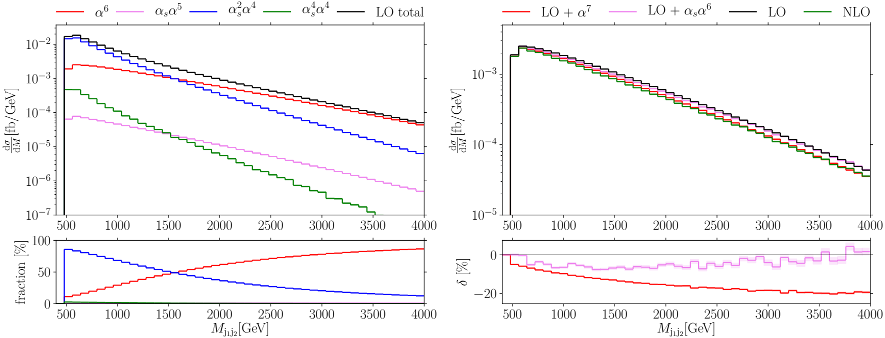
Process	Total [fb]	$\mathcal{O}(\alpha_s^4\alpha^4)$ [%]	$\mathcal{O}(\alpha_s^2\alpha^6)$ [%]	$\mathcal{O}(\alpha_s\alpha^5)$ [%]	$\mathcal{O}(\alpha^6)$ [%]	Remark
$\mathrm{W^+W^+}$	1.63	—	10.5	2.9	86.7	
$\mathrm{W^+Z}$	1.36	—	80.7	0.5	18.8	
ZZ	0.22	5.9	59.5	2.4	32.2	no $\Delta y_{\mathrm{j_1 j_2}}$ cut
$\mathrm{W^+W^-}$	9.87	2.0	70.0	0.7	27.3	

- $\mathrm{W^+W^+}$: more signal than background, although naively $\alpha_s^2\alpha^4 \gg \alpha^6$
- more Z-bosons, less cross section
- less charge, more gluons ⇒ more background
- $\mathcal{O}(\alpha_s^4\alpha)$: loop-induced 4-gluon processes

Results from:

- $\mathrm{W^+W^+}$: [B. Biedermann, A. Denner, M. Pellen]
- $\mathrm{W^+Z}$: [A. Denner, S. Dittmaier, P. Maierhöfer, M. Pellen, C.S.]
- ZZ: [A. Denner, R. Franken, M. Pellen, T. Schmidt]
- $\mathrm{W^+W^-}$: [A. Denner, R. Franken, T. Schmidt, C.S.]

Differential distributions for $\mathrm{W}^+\mathrm{W}^-$ VBS



- starting at $M_{\mathrm{j}_1\mathrm{j}_2} \approx 1500\,\mathrm{GeV}$ EW and QCD production cross
- size of the 4 gluon loop-induced up to 4.5 %
- $\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$ comparatively small
- $\mathcal{O}(\alpha^7)$ as large as −20 % of the *total* LO

EW corrections for VBS cross sections

Process	$\mathrm{W^+W^+}$	$\mathrm{W^+Z}$	ZZ	$\mathrm{W^+W^-}$
$\sigma^{\alpha^7}_{\mathrm{NLO}}$[fb]	$-0.2169(3)$	$-0.04091(2)$	$-0.015573(5)$	$-0.307(1)$
$\sigma^{\alpha^6}_{\mathrm{LO}}$[fb]	$1.4178(2)$	$0.25511(1)$	$0.097683(2)$	$2.6988(3)$
δ^{α^7}[%]	-15.3	-16.0	-15.9	-11.4

- EW corrections, $\delta^{\alpha^7} = \sigma^{\alpha^7}_{\mathrm{NLO}}/\sigma^{\alpha^6}_{\mathrm{LO}}$, for VBS processes typically $-15\,\%$ to $-16\,\%$
- understood from EW logs [A. Denner, S. Pozzorini]:

$$\delta_{\mathrm{EW,LL}} \approx \frac{\alpha}{4\pi}\left\{-4C^{\mathrm{EW}}_{\mathrm{W}}\log^2\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)+2b^{\mathrm{EW}}_{\mathrm{W}}\log\left(\frac{Q^2}{M_{\mathrm{W}}^2}\right)\right\}$$

- with $C^{\mathrm{EW}}_{\mathrm{W}} = 2/\sin\theta_{\mathrm{w}}$, $b^{\mathrm{EW}}_{\mathrm{W}} = 19/6\sin\theta_{\mathrm{w}}$, $Q = M_{4\ell}$, usually $\langle Q^2\rangle \approx 400\,\mathrm{GeV}$

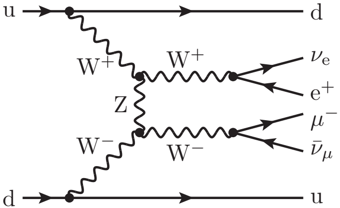
→ How is $\mathrm{W^+W^-}$ VBS special?

$\mathrm{W}^+\mathrm{W}^-$: VBS mixing with Higgs VBF

Is $\mathrm{pp} \to \mathrm{e}^+\nu_\mathrm{e}\mu^-\bar{\nu}_\mu\,\mathrm{jj}$ VBS or Higgs VBF?

$$Q = M_{4\ell}$$

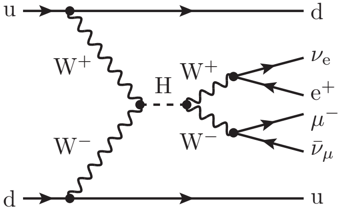
VBS:



$\langle Q \rangle \approx 400\,\mathrm{GeV}$

vs.

Higgs VBF:



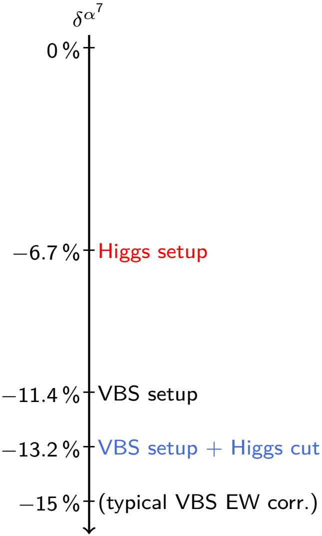
$\langle Q \rangle \approx 125\,\mathrm{GeV}$

→ We sum the diagrams, so it's both

- more Higgs VBF lowers $\langle Q^2 \rangle$ from 400 GeV towards $M_\mathrm{H} = 125\,\mathrm{GeV}$ and thus
- lowers the size of EW corrections
- more VBS increases $\langle Q^2 \rangle$ towards 400 GeV and
- increases the size of EW corrections towards the $-15\,\%$

→ we can test this!

$\mathrm{W}^+\mathrm{W}^-$ VBS and Higgs VBF: $\delta^{\alpha^7} = \sigma^{\alpha^7}_{\mathrm{NLO}}/\sigma^{\alpha^6}_{\mathrm{LO}}$



δ^{α^7}

$0\,\%$

$-6.7\,\%$ Higgs setup

$-11.4\,\%$ VBS setup

$-13.2\,\%$ VBS setup + Higgs cut

$-15\,\%$ (typical VBS EW corr.)

Increase Higgs VBF (Higgs setup): we force the Higgs on-shell: $\mathrm{pp} \to H\mathrm{jj} \to 2\ell 2\nu\mathrm{jj}$

$$60\,\mathrm{GeV} < M_{\mathrm{T},2\ell,2\nu} < 125\,\mathrm{GeV}$$

$$|M_{2\ell 2\nu} - M_{\mathrm{H}}| > 20\Gamma_{\mathrm{H}}$$

VBS setup + Higgs cut removes 98 % of the Higgs BW peak

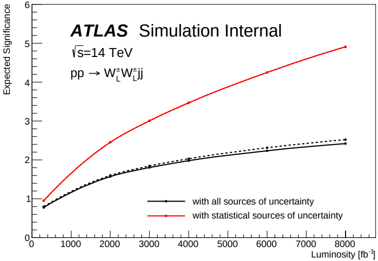
→ a sizable fraction (27 %) of Higgs VBF mixes with opposite-sign VBS!

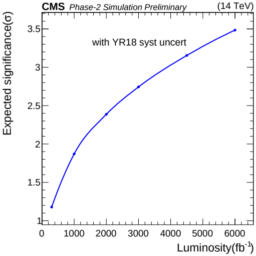
→ mostly responsible for smaller corrections (see table in backup slides)

Part II. Miscellanea

Important: beyond fixed-order

- matching to parton showers [A. Ballestrero et al.] [M. Chiesa, A. Denner, J.-N. Lang, M. Pellen]
- large EW corrections → automated resummation of Sudakov logarithms [E. Bothmann, D. Napoletano, M. Schönherr, S. Schuhmann, S. Luca] [A. Denner, S. Rode]
- EFT → Giacomo's talk
- polarized observables @ NLO: access longitudinal polarizations, (more) direct test of EWSB





- see Rene's and Joany's talk yesterday
- VBS at LO: [A. Ballestrero, E. Maina, G. Pelliccioli], [A. Ballestrero, E. Maina, G. Pelliccioli], [A. Ballestrero, E. Maina, G. Pelliccioli], [D.B. Franzosi, O. Mattelaer, R. Ruiz, S. Shil]

→ talk by Diana later today

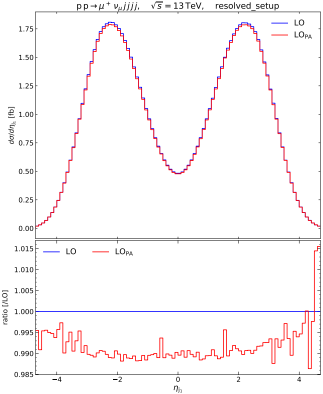
Outlook: semi-leptonic VBS channels

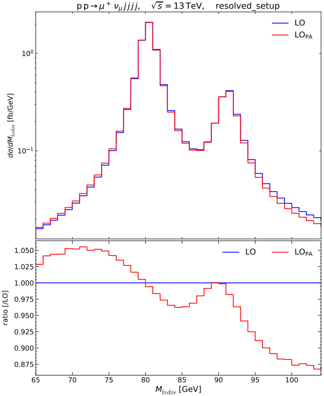
$\mathrm{pp} \to \ell^+\ell^-\mathrm{jjjj} + X$ and $\mathrm{pp} \to \ell^+\nu_\ell\mathrm{jjjj} + X$ @ $\mathcal{O}(\alpha^6)$:

- necessarily sums $\mathrm{W^+W^+}$, $\mathrm{W^+Z}$ and $\mathrm{W^+W^-}$
- 192 partonic channels at $\mathcal{O}(\alpha^6)$
- NLO is going to be challenging

Preliminary results:

- larger cross section: 2.5 fb (boosted) 10 fb (resolved)
- setup from [CMS collaboration], see Nurfikri's talk yesterday
- preliminary results, comparing $\mathcal{O}(\alpha^6)$ fully off-shell vs. pole approximation (PA)





How do we make our predictions useful for the experiment?

- Dominant $\mathcal{O}(\alpha^7)$ corrections expensive, can't be done with MCs like Madgraph5_aMC@NLO
- MoCaNLO produces histograms for arbitrary observables $\mathcal{O}$ into *n* bins:

$$\left\{ \mathcal{O}_{\mathrm{L}}^{i},\ \mathcal{O}_{\mathrm{R}}^{i},\ \frac{1}{\mathcal{O}_{\mathrm{R}}^{i}-\mathcal{O}_{\mathrm{L}}^{i}} \int_{\mathcal{O}_{\mathrm{L}}^{i}}^{\mathcal{O}_{\mathrm{R}}^{i}} \mathrm{d}\mathcal{O} \frac{\mathrm{d}\sigma}{\mathrm{d}\mathcal{O}} \right\}_{i=1}^{n}$$

- time-consuming, but straightforward: rerun for other cuts and bin limits
- MoCaNLO can't produce unweighted events: technical limitation

Possible avenues with Madgraph5_aMC@NLO/SHERPA:

- run it with Sudakov logs [E. Bothmann, D. Napoletano] [D. Pagani, M. Zaro] [D. Pagani, T. Vitos, M. Zaro]
- compare against exact results
- if agreement is found, use it and reweight

Part III. Conclusions

Summary

- calculations for the whole NLO tower done for almost all VBS channels
- $\mathcal{O}(\alpha_{\mathrm{s}}^2\alpha^5)$ missing for $\mathrm{W}^+\mathrm{Z}$ and $\mathrm{W}^+\mathrm{W}^-$
- EW corrections to VBS are universally $-15\,\%$ to $-16\,\%$, if no significant overlap with other processes
- such a case is $\mathrm{W}^+\mathrm{W}^-$: Higgs VBF

Outlook/wishlist:

- semi-leptonic VBS channels
- matching to parton showers
- polarized predictions
- . . . in a form easily usable by the experiments

Questions?

No Higgs integrated results

VBS cross sections with additional Higgs cut:

Contribution	$\sigma^{\alpha^6}_{\mathrm{LO}}$[fb]	$\Delta\sigma^{\alpha^7}_{\mathrm{NLO}}$[fb]	δ^{α^7}[%]	$\Delta\sigma^{\alpha_{\mathrm{s}}\alpha^6}_{\mathrm{NLO}}$[fb]	$\delta^{\alpha_{\mathrm{s}}\alpha^6}$[%]
VBS only	1.6117(2)	$-0.239(2)$	-14.8	$-0.043(3)$	-2.7
VBS + WWW	0.11398(2)	$-0.0143(2)$	-12.5	0.0080(5)	7.1
VBS + WWZ	0.24916(4)	$-0.0324(3)$	-13.0	0.0018(11)	0.1
WWW only	$5.303(2) \times 10^{-5}$	$-1.43(2) \times 10^{-5}$	-27.0	0.01110(2)	2.1×10^{4}
WWZ only	$9.415(2) \times 10^{-5}$	$-2.80(2) \times 10^{-5}$	-29.7	0.004021(3)	4.3×10^{3}
$\gamma\gamma/\gamma\mathrm{g}$	$6.832(4) \times 10^{-6}$	0.02575(3)	3.8×10^{5}	0.0108(2)	1.6×10^{5}
total	1.9750(2)	$-0.260(2)$	-13.2	$-0.007(3)$	-0.4

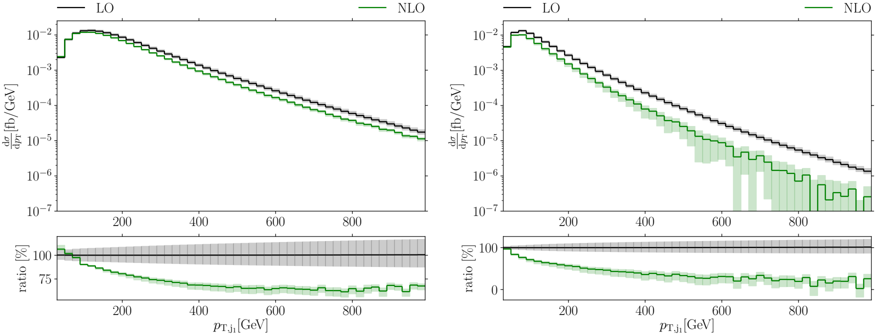
NLO coupling tower: $\mathrm{pp} \to \mu^+\nu_\mu 4\mathrm{j} + X$

- the process $\mathrm{pp} \to \mu^+\nu_\mu 4\mathrm{j} + X$ contains up to 3 quark lines
- can exchange 0, 1, 2 gluons between them $\Rightarrow$ more complicated NLO tower

$$\begin{tikzcd}
 & & \text{2 internal gluons} \arrow[d] & & & & \text{1 internal gluon} \arrow[d] & & & & \text{0 internal gluons} \arrow[d] & \\
\textbf{LO}: & & \mathcal{O}(\alpha_{\mathrm{s}}^4\alpha^2) \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \mathcal{O}(\alpha_{\mathrm{s}}^3\alpha^3) \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \mathcal{O}(\alpha_{\mathrm{s}}^2\alpha^4) \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \mathcal{O}(\alpha_{\mathrm{s}}^1\alpha^5) \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & & \mathcal{O}(\alpha_{\mathrm{s}}^0\alpha^6) \arrow[dl, "\text{QCD}"'] \arrow[dr, "\text{EW}"] & \\
\textbf{NLO}: & \mathcal{O}(\alpha_{\mathrm{s}}^5\alpha^2) & & \mathcal{O}(\alpha_{\mathrm{s}}^4\alpha^3) & & \mathcal{O}(\alpha_{\mathrm{s}}^3\alpha^4) & & \mathcal{O}(\alpha_{\mathrm{s}}^2\alpha^5) & & \mathcal{O}(\alpha_{\mathrm{s}}^1\alpha^6) & & \mathcal{O}(\alpha_{\mathrm{s}}^0\alpha^7)
\end{tikzcd}$$

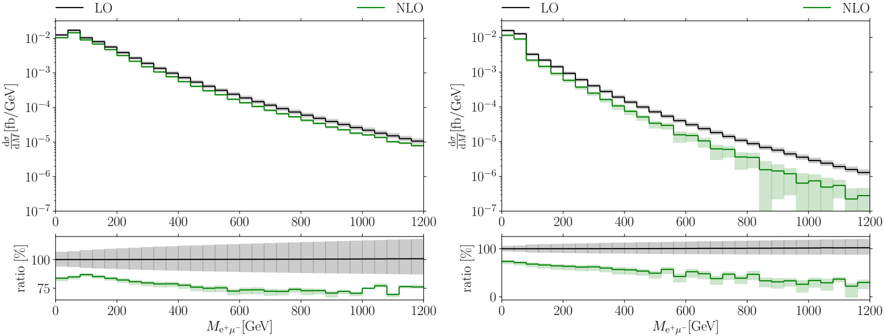
- $\mathcal{O}(\alpha_{\mathrm{s}}^4\alpha^2)$, $\mathcal{O}(\alpha_{\mathrm{s}}^2\alpha^4)$ and $\mathcal{O}(\alpha^6)$ calculated in [A. Ballestrero, G. Bevilacqua, E. Maina]
- $\mathcal{O}(\alpha_{\mathrm{s}}^5\alpha^2)$: [C.F. Berger et al.]

NLO distributions: transverse momentum of the leading jet



- left: VBS-, right: Higgs-setup
- band indicates 7-point scale uncertainties

NLO distributions: dilepton invariant mass



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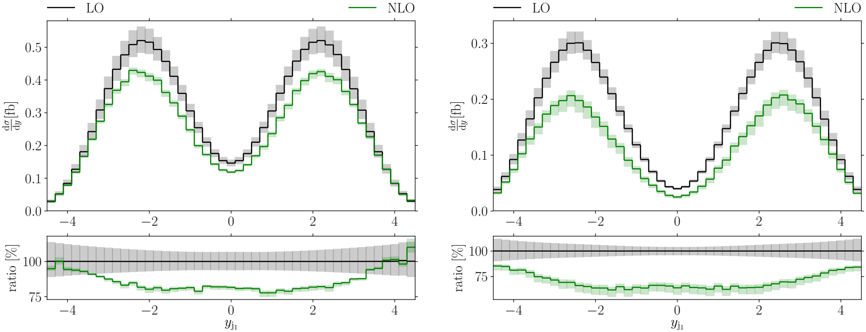
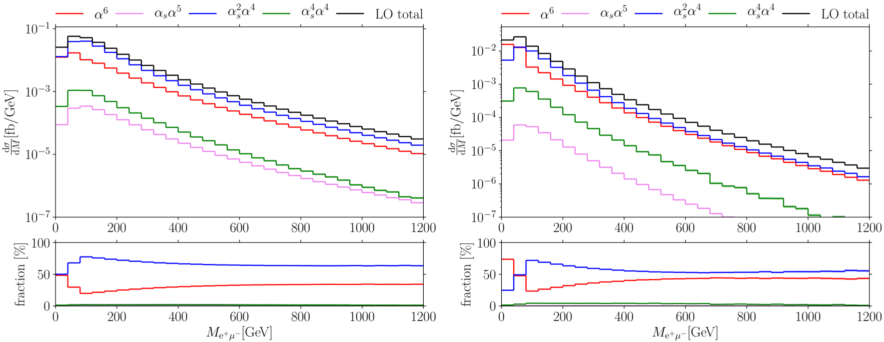
- band indicates 7-point scale uncertainties

NLO distributions: leading jet rapidity



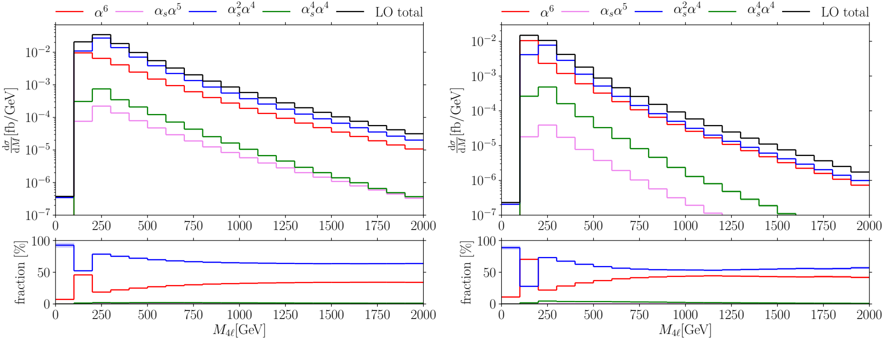
- left: VBS-, right: Higgs-setup
- band indicates 7-point scale uncertainties

LO distributions: dilepton invariant mass



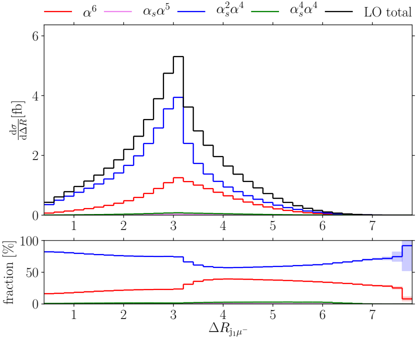
- left: VBS-, right: Higgs-setup
- band indicates MC integration uncertainties

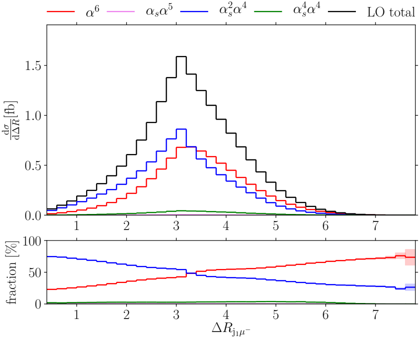
LO distributions: four-lepton invariant mass



- left: VBS-, right: Higgs-setup
- band indicates MC integration uncertainties

LO distributions: Leading-jet–muon distance





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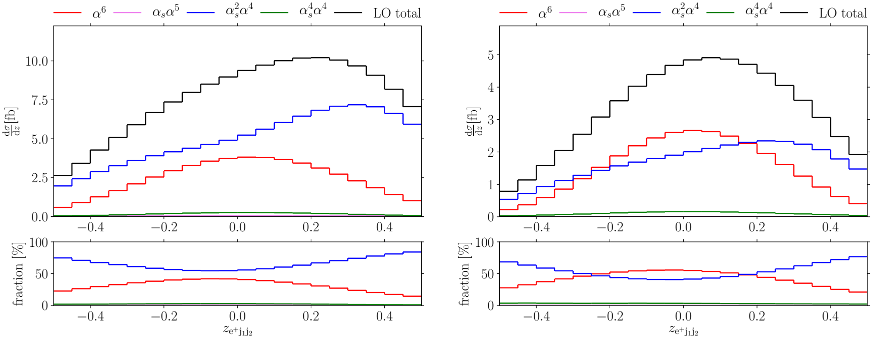
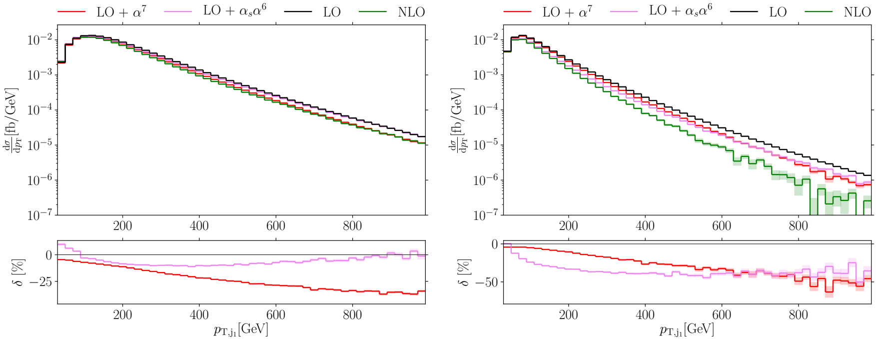
LO distributions: Centrality of the positron



- left: VBS-, right: Higgs-setup
- band indicates MC integration uncertainties

NLO distributions: leading jet transverse momentum



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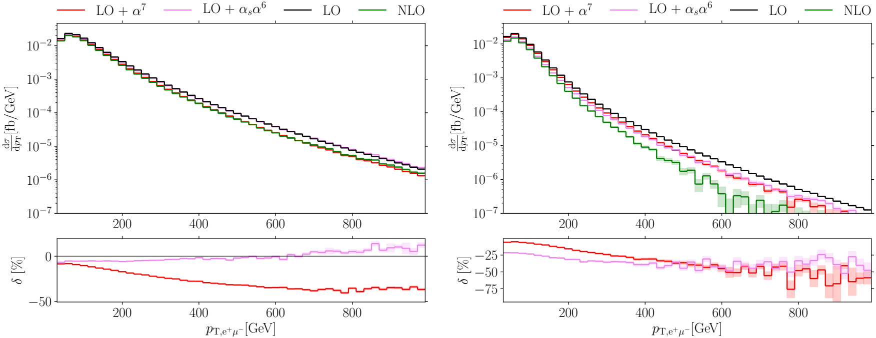
NLO distributions: dilepton transverse momentum



- left: VBS-, right: Higgs-setup
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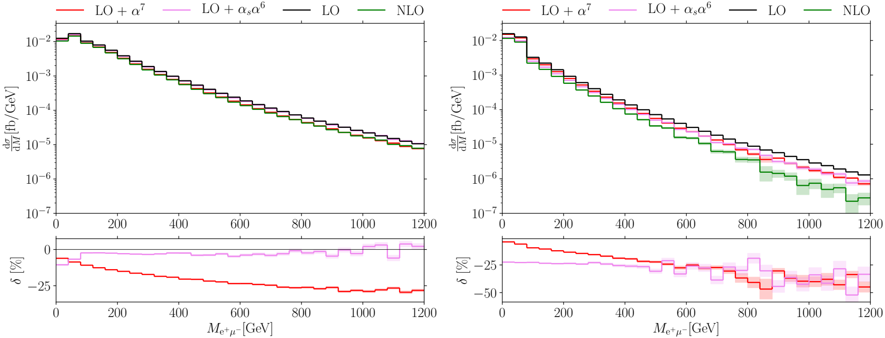
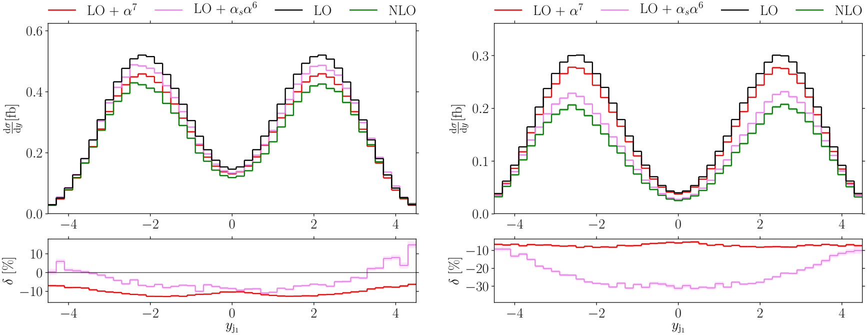
NLO distributions: dilepton invariant mass



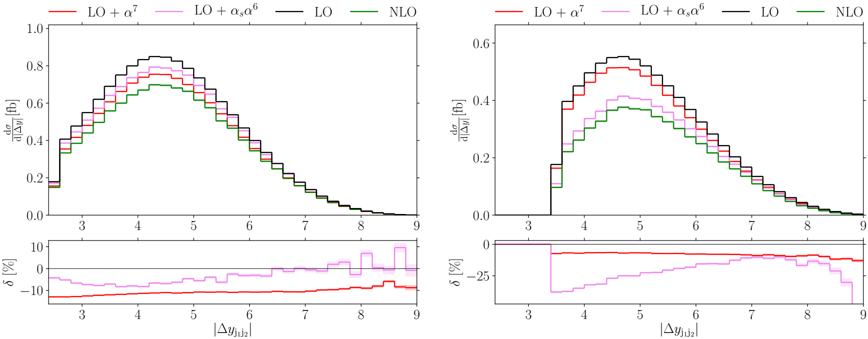
- left: VBS-, right: Higgs-setup
- band indicates MC integration uncertainties

NLO distributions: leading jet rapidity



- left: VBS-, right: Higgs-setup
- band indicates MC integration uncertainties

NLO distributions: leading jet rapidity separation



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